Dane Philip John Hull – Final Year Thesis as part of a Bachelor of Engineering (Naval Architecture), Australian Maritime College, University of Tasmania.

Speed Sailing Design & Velocity Prediction Program

Nomenclature

Symbol	Description	Units
α	Incidence	°
λ	Leeway angle	°
γ	Tack/Gybe angle	°
ϕ	Heel angle	°
ρ	Density	kg/m^3
A	Area	m^2
CD	Drag coefficient	
CL	Lift coefficient	
D	Drag	N
DW	Windage drag	N
DWL	Design Water Line	m
Fx	Force in the x direction	N
Fy	Force in the y direction	N
Fz	Force in the z direction	N
k	Form factor	
L	Lift	N
Mx	Moment in the x direction	N.m
My	Moment in the y direction	N.m
Mz	Moment in the z direction	N.m
V	Velocity	m/s
Vs	Hull speed	m/s
Vw	Wind speed	m/s

Acronyms

AOA	Angle Of Attack
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
CG	Centre Of Gravity
COA	Centre Of Area
COE	Centre Of Effort
DOF	Degrees Of Freedom
DWL	Design Waterline
GPS	Global Positioning System
IMCA	International Moth Class Association
IMS	International Measurement System
SOG	Speed Over Ground
TWA	True Wind Angle
TWS	True Wind Speed
VPP	Velocity Prediction Program

Abstract

In recent years the performance of high speed sailing craft has been increasing rapidly. One reason for this rapid development is the introduction of hydrofoils to high speed sailing craft, this has allowed sailing craft such as l'Hydroptere to reach speeds in excess of 60 knots, Hydroptere [2010].

The International Moth Class dinghy is perhaps the most significant example of these high performance craft. The performance of these craft is to be determined by the development and use of a Velocity Prediction Program (VPP). This investigation uses experimental and theoretical studies to estimate the gravitational, aerodynamic and hydrodynamic forces acting on the moth while sailing. Lift and drag data for the lifting foils are predicted using experimental results by Binns et al. [2008], at the Australian Maritime College, Tasmania. These forces are used in a force balance to predict the performance of the moth sailing dinghy, the program used to solve for equilibrium conditions is FutureShip Equilibrium.

The results of the VPP are validated using Global Positioning System (GPS) data from a race tracking website, TracTrac [2011]. Boat speed and true wind angle (TWA) data is obtained from the race tracking website, TracTrac [2011] and wind speed data from a weather history website, Wunderground [2010].

1. Introduction

1.1. High Speed Sailing

There have been many changes to the approach to high speed sailing in recent years, one of which has been the introduction of hydro-foils. The introduction of hydro-foils has led to sailing vessels being capable of speeds in excess of 60 knots, Hydroptere [2010] but however has led to an inherently unstable platform.

The most significant example of these vessels is the International Moth Sailing Dinghy. Moths are now capable of speeds of over 30 knots, however because of the unstable nature of the moth, sailors are deterred from pushing their boats to the limit for fear of damage.

A method to determine the probability of the boat to become unstable is needed. In order to resolve this problem the speed and trim is needed for a particular heading. Therefore a Velocity Prediction Program (VPP) is required.

1.2. Background

Studies into the performance of hydrofoil moths have been conducted ever since their introduction in the mid 1980's, Mothosphere [2010]. These studies have been largely trial and error investigations which have resulted in a somewhat standard setup consisting of twin T-foils, with a wand controlled flap on the main foil and a skipper controlled flap on the rudder. This development is partially due to restrictions on multihulls adopted by the moth class rules, ISAF [2007]. These rules limited the development of early surface piercing V-foil designs.

Tow tank tests conducted by Binns et al. [2008], measured lift and drag data on a surface piercing T-foil at various angles and depths. These studies were conducted specifically for moth rudder foils, however both rudder and main foil designs are essentially the same. A study into the effects of Froude, Weber and Cavitation numbers on ventilation of surface piercing T-foils has also been conducted by Emonson [2009]. A study into the effects of yawed surface piercing struts was conducted by Breslin and Skalak [1959], methods and boundaries to avoid ventilation are outlined in the paper. Studies can be applied to determine the foils probability of ventilating.

A method by Bogle [2010], details the development of a VPP for a hydrofoil moth dinghy. This method will be used as a basis program for the development of this VPP. This VPP relies on the use of different solver settings within FutureShip to allow the solver to reach an equilibrium condition in both foiling and non-foiling conditions. A similar study conducted at the University of Southampton by Findlay and Turnock [2008] investigates the use of a VPP to study the effects of differing foil arrangements on moth dinghies. This study will be used to model techniques by sailors to temporarily increase sail power to enable foiling to occur, however it does not account for windward heel angles when sailing to windward.

Foil data from tow tank testing by Binns et al. [2008] will be used in place of numerical methods used by Bogle [2010]. Full scale hull aero dynamic and hydro dynamic measurements were taken by Beaver and Zseleczky [2009]. These measurements were taken for foiling and non-foiling conditions and can be used to validate the results of the VPP.

Lift and drag coefficients for varying sail types such as wing mast single skin, double skin and pocket luff sails are investigated using experimental methods by Marchaj [1996]. Current moth sails consist of a pocket luff and full cambered battens, this style of sail has a similar profile to a wing mast and single skin sail. Sail data for solid wing sails have also been analysed by Marchaj [1996]. Using this data, the performance of a wing sail moth can be found. Development of a wing sail for a moth is currently being investigated, as seen at the 2011 Moth world championships Grimm [2011].

1.3. Project Objective

High speed sailing craft differ widely in both design and performance aspects. The aim of this project is to develop a performance prediction method capable of producing accurate results for a wide range of high performance sailing designs.

A designer of high speed sailing craft is faced with many possible designs ranging from kite and sail boards to large hydrofoil multihulls. It is important for the designer to be able to test the performance of their design before it is produced, so as to ensure it is the best possible given the design parameters.

Due to the varied and complex nature of high speed sailing craft, this project will use a simple craft for development, the International Moth sailing dinghy.

1.4. Moth Sailing Dinghy

The international moth class dinghy was first designed in 1928 by Len Morris in Victoria Australia as a simple flat bottomed scow. The class now is governed by an international body, the International Moth Class Association (IMCA), IMCA [2008] and is one of the most advanced sailing boat classes in the world. The moth is a development class, the rules enable the designer to have much freedom when designing the boat. The international class rules, ISAF [2007] are summarised below in Tab. 1.1. These freedoms have now led to the typical moth class dinghy being very narrow, with large hiking wings and fitted with hydrofoils.

Table 1.1.: International moth class rules

Rule	Dimension
Maximum Length	3355mm
Maximum Beam	2250mm
Maximum Luff Length	5600mm
Maximum Sail Area	$8m^2$
Minimum Displacement at DWL	70kg

The hydrofoil system first designed by John Illett of Western Australia, Mothosphere [2010], consists of twin surface piercing T-foils, one each on the centre board and rudder. Both of the T-foils have a movable foil or elevator flap to control the lift produced by each foil. The main hydrofoil is controlled by a sensor wand mounted on the bow of the boat to adjust the flap angle with changes to the boats height above the water surface. The rudder foil is controlled by the skipper via a rotating tiller extension to adjust the flap angle, this is primarily used to trim the boat while at full flight. This concept is illustrated below in Fig. 1.2, diagram by Jason Lee, Schmidt [2007].

1.5. Methodology

Velocity Prediction Programs (VPP) are very common practice in the world of yacht design, however most do not allow the use of hydrofoils. The VPP FutureShip Equilibrium, is an open modular style program based on programmable force modules, FutureShip [2010]. FutureShip Equilibrium comes with a large range of predefined force modules as well as the potential for additional force modules which can be programmed using common programming languages. The program will then find the equilibrium state give a set of input parameters, this is typically used to find the speed of a vessel at a particular point of sail.

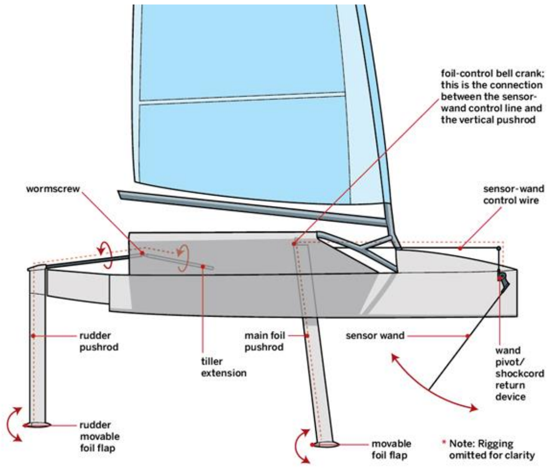

Figure 1.2.: Moth hydrofoil configuration, Schmidt [2007]

To find the speed of a hydro foiled moth, all the components affecting the forces on the hull need to be considered. Fig. 1.3 below shows the breakdown of forces affecting the boat.

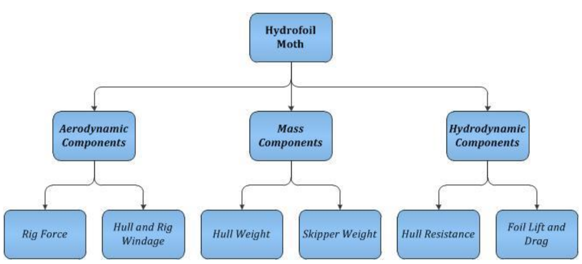

Figure 1.3.: Force components on a hydrofoil moth

1.6. Validation

One reason for choosing the International Moth for the development of a VPP is for ease of validation. There have been full scale tests of both hulls and foils being conducted at maritime facilities around the world, Beaver and Zseleczky [2009]. This enables readily available comparisons between VPP results and full scale data.

Due to the advances in GPS technology, many sailing races can be tracked live via the internet, TracTrac [2011]. This data is saved and can be easily accessed to watch past sailing regattas. The data given is a speed log of each individual boat in the fleet, given a SOG. The boats course is given as a trailing line, wind direction can be determined using the boats tack or gybe angle.

2. Velocity Prediction

Velocity prediction is done by means of a force balance, where a set of non-linear equations are solved, one for each degree of freedom in the VPP model. These equations define the forces and moments acting on the hull, rig and foils.

The forces acting on the hull and rig are determined by the wind angle, yaw, wind and boat speed. The program then aims to maximise boat speed using trim variables such as sail trim.

2.1. Force Balance

The forces and moments on each axis on the force balance are summed to zero for equilibrium. The following equations represent equilibrium in all six degrees of freedom.

Hull resistance and sail drive are represented by 2.1. Sail drive is maximised by the sailor in order to achieve maximum boat speed. Heeling and restoring moments are represented by 2.2. A side effect of maximising sail drive is the increasing of the heeling moment, this is counteracted by the sailors mass moment.

$$\sum F_X = 0 \qquad (2.1)$$

$$\sum M_X = 0 \qquad (2.2)$$

Sail and hull side forces are represented by 2.3. The sail side force is opposed by lift created by the hull and foils. Trimming moments are accounted for in 2.4. These are caused by differences in centres of weight and buoyancy as well as lifting foil moments.

$$\sum F_Y = 0 \quad (2.3)$$

$$\sum M_Y = 0 \quad (2.4)$$

Mass and buoyancy forces are represented by 2.5. Foil lifting forces are also included in this equation. Yaw moments 2.6 due to differences between the centres of sail and submerged area, also rudder angles influence the equilibrium of the equation.

$$\sum F_Z = 0 \quad (2.5)$$

$$\sum M_Z = 0 \quad (2.6)$$

Simple VPP's which use only three degrees of freedom, Larsson and Eliasson [2007] use 2.1, 2.2 and 2.3, these represent boat speed, leeway and heel angles. These three operating conditions are what the VPP is solving for. By increasing the degrees of freedom of the model accuracy, complexity and solving time increase.

2.2. Design Criteria and Parameters

In order to predict the speed and performance of a hydrofoil moth many aspects of the boat and sailing technique must be modelled within the VPP to gain meaningful results.

The forces acting on a sailing dinghy are complex, particularly in the case of a hydrofoil, where the boat is inherently unstable. The sailor must make many adjustments to weight position, foil, rudder and sail trim in order to keep the boat sailing fast. These adjustments must be modelled in the VPP.

The skipper's mass needs to be moved both longitudinally and transversely around the boat, since the skipper's mass makes up approximately 70% of the total mass, it is the main influence on trimming and heeling moments. Moths typically sail close hauled with a negative heel angle, opposite to that of a traditional sailing yacht, Grimm [2011]. Here the lift produced by the main and rudder foils is used to reduce or in some cases reverse the need of leeway angle. The skipper's weight is also used to increase the angle of attack (AOA) on the foils to assist with take-off in low speed circumstances.

The design of the lifting foil system on a moth is somewhat complex. Although the mechanics of the system are relatively simple, they must provide the correct amount of lift for four different sailing conditions.

Non-Foiling: The non-foiling condition in moth sailing is when the moth does not have enough boat speed for take-off. This typically comes about when sailing in light airs, close hauled (AWA $< 35^\circ$) and square (AWA $= 180^\circ$). At this stage, it is desired that the lift of the foils be minimised to reduce drag as there is no chance of the boat being able to take off.

Take Off: For a typical hydrofoil moth dinghy, take off occurs in about 7 knots of breeze at an AWA $\approx 90^\circ$. In this condition the lifting foil must create significant lift. As this lift decreases the draft of the moth, hull resistance decreases thus increasing speed. This in turn increases lift and the process continues until the hull is lifted clear of the water's surface. Once the hull is clear of the water surface the foils lift must be decreased to maintain the desired flying height equilibrium.

Design Speed: This is the speed range at which the foil operates at flying height with a minimum of drag. Hydrodynamic drag minimal as the hull is flying clear of the water, the major drag component becomes windage from the hull and rig. It is assumed that full vertical force is supported by the main foil and the sailor adjusted rudder foil is used to maintain the boats trim.

Maximum Speed: The maximum speed condition should be such that any further increase in speed will lead to ventilation of the foils and therefore crashing. It may be necessary to have a negative flap angle on the main foil to maintain the correct lift force due to high speed.

Main Foil Flap Control

Adjustments to the main foils lift is done using a wand setup, shown in Fig. 1.2. The wand is mounted on the bow of the boat, where it is forced to rotate so that the tip is in contact with the water surface. The wand is connected to the main foil flap using a Bowden cable. For this VPP, the action of this wand will be simply represented by a lift variation with height relationship.

Rudder Foil Flap Control

The rudder foil is used to adjust trim in foiling conditions, Schmidt [2007]. The trim is adjusted by the skipper via a twisting grip on the tiller extension, this adjustment alters either the AOA of the rudder foil or an elevator flap on the trailing edge of the rudder foil. The rudder itself is used to steer the boat, it is often used to alter the boat's course for a short period of time to sail the boat at a faster angle in order to achieve a foiling condition before returning to the required course.

Skipper Location Control

Skipper location is the only source of righting moment available when sailing a hydrofoil moth. The skipper will move transversely in order to counter the sails heeling moment and sail the boat at the desired heel angle. The skipper will also move longitudinally to adjust the trim of the boat. The trim of the boat directly effects the lifting foils incidence angle and is used to produce maximum lift to assist the boat to take off.

Sail Flat Control

Sail trim is used to alter the sail power. Typically the maximum power available will be utilised by the skipper, however it is also used to adjust the heel angle when no further righting moment is available, thus the skipper is hiking out as far as possible.

2.3. FutureShip Equilibrium

Body Fixed Coordinate System

FutureShip Equilibrium uses a body fixed coordinate system to input the position where forces on the boat are acting, this is a coordinate system which is fixed with respect to the boat itself. Fig. 2.1 shows the origin point and directions for each of the x, y and z axes, moments about each of these axes are also shown. These moments are Mx, My and Mz respectively.

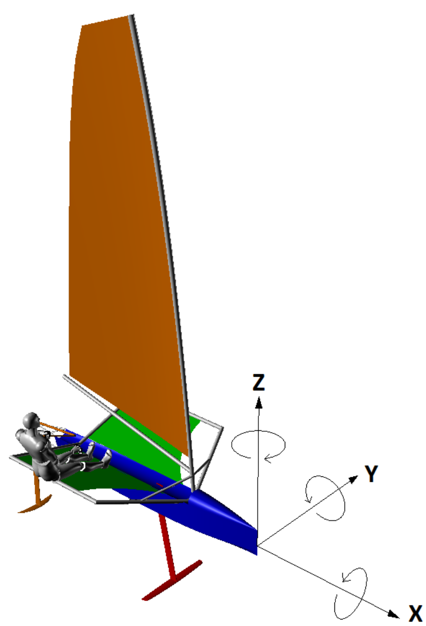

Figure 2.1.: Body fixed coordinate system

Force Modules

Force modules are used to break down the simulation of the boat into pieces which are easily predicted. These modules can be divided into three sections:

Gravity Forces on a moth are that of the fixed mass of the boat and the mass of the skipper which must move to trim the boat as required.

Aerodynamic Forces on a moth are the many drag forces produced by the hull and rig, as well as the major lift force produced by the sail.

Hydrodynamic Forces on a moth consist of the hull buoyancy, as well as lift and drag produced by the hull and foils.

It needs to be considered that within these modules, in particular those representing the lifting surfaces of the centreboard and rudder, that there needs to be some representation of the control of lift or otherwise by either human or mechanical means. That is, the main foil typically controlled by a wand to adjust the lift produced by this foil must be correctly represented. Also the lift of the rudder is typically controlled by the skipper, therefore the skipper's use of this control must be determined in order to model the effect correctly.

Input Data

Data input into FutureShip Equilibrium consists of both boat and environmental data. Boat data is input through the many force modules that represent the many aspects of the sailing boat. Environmental data is typically the conditions in which the boat is to be tested, the main data of which is TWS and TWA.

Gravity Forces

Moth Mass: A weight estimate was carried out to find the total mass of the fully rigged moth. This data is used to input the mass and centre of gravity of the moth in body fixed coordinates.

Skipper Mass: The weight of the skipper input is 80kg, the maximum competitive weight of a moth sailor. The position of this mass is input as a range in both the x and y direction, as the skipper is able to shift their weight to trim the boat.

Aerodynamic Forces

Rig Force: For the calculation of rig force, data from the IMS VPP, Claughton et al. [1998] have been used to estimate mainsail lift and drag coefficients. The coefficients have then been scaled to resemble the maximum lift produced by a streamlined mast and single skin sail, Marchaj [1996].

Windage: Windage is calculated by using profile, plan and body areas above the waterline as well as their associated geometric centres. A drag coefficient (C_D) of 1.13 has been used to estimate the drag around the varying geometries that make up this drag force, Larsson and Eliasson [2007].

Hydrodynamic Forces

Buoyancy Force: The hull geometry has been input into the buoyancy force module using a hull geometry definition file (.shf).

Centreboard and Rudder Force: The lift and drag produced by the centreboard and rudder are defined in two separate modules. These modules detail the area, COE, CL and CD based on their planform area and sectional shape.

Main and Rudder Lifting Force: Similar to the centreboard and rudder modules above, the main and rudder lifting foils are defined using the area, COE, CL and CD for each foil. However additional variables have been added to represent the action of the "wand", skipper and distance of the lifting foil to the water surface.

Main Foil Data

The lift and drag force produced by the main foil are calculated using an equation derived from experimental results conducted by Binns et al. [2008]. In this method the lift and drag coefficient are calculated using 2.7 and 2.8, where the coefficients A, B, C and D have been derived experimentally. The coefficients are plotted with respect to the depth to chord ratio and at a constant Froude number (F_n) of 3.4.

$$CL = A.\alpha + B \quad (2.7)$$

$$CD = C.C_L^2 + D \quad (2.8)$$

The added lift and drag due to the wand controlled elevator flap is calculated with respect to the flap angle, this is directly proportional to the boat's flying height. A curve has been derived to determine the foil's flap angle as a function of flying height, this curve has been derived to represent the wand setup to adjust the main foil flap angle.

The added lift and drag due to flap angle as determined from XFOIL are shown below in Fig. 2.7 and Fig. 2.8. As this data is determined for two dimensional sections only, some error will be present due to three dimensional effects.

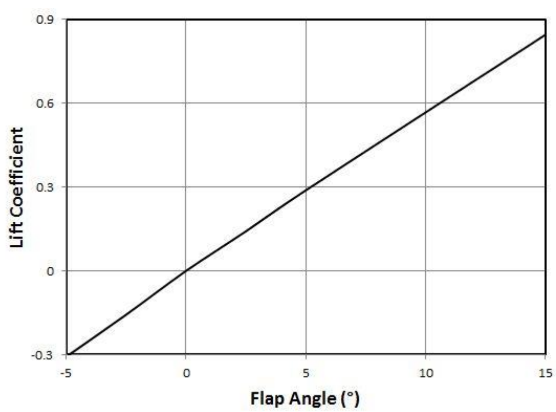

Figure 2.7.: Lift due to foil flap angle

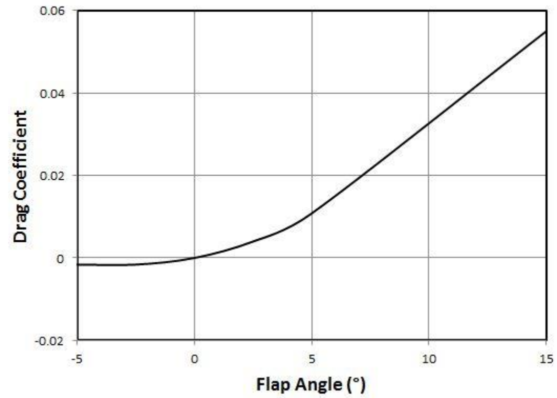

Figure 2.8.: Drag due to foil flap angle

Rudder Foil Data

The lift and drag force produced by the rudder foil are also calculated using the equations 2.7 and 2.8.

Similar to the main foil, the added lift and drag due to the skipper controlled elevator flap is calculated with respect to the flap angle.

2.4. Results Interpretation

The output of a VPP is typically in the form of a polar plot, where the tangential axis represents the TWA relative to the boat, a performance measurement such as speed, yaw or heel angle is shown on the radial axis. Varying wind speeds plotted on the same graph gives a good representation of target speeds to the sailor. Also in the case of the foiling moth, can show the conditions in which the boat should be flying.

3. Validation

3.1. Moth Race Data

As mentioned previously, the VPP will be validated using GPS moth race data compiled from the internet, TracTrac [2011]. As moth racing is conducted on a windward/leeward course (directly upwind and downwind), only two points on the VPP polar plot will be available. These points will be the points with the highest VMG for both windward and leeward legs.

In order to compare predicted VPP data with actual moth data the boat speed (V_s), true wind angle (TWA) and wind speed (V_w) is required. The boat speed (V_s) can be taken directly from TracTrac [2011], the wind speed (V_w) and true wind angle (TWA) must be estimated. The data has been gathered from the 2010 Sail Sydney Regatta held on Sydney Harbour in December 2010. To gather the required data, the race is replayed and paused at a specific time, when the required boats are sailing in clear air and at the required TWA. To do this only four boats have been used to validate the VPP, these have been the first four boats in the fleet to ensure their sailing technique is as close to optimal as practical. To gather the validation data, a screen shot is taken at the required point in the race whereby the data can be extracted. The boat speed (V_s) can be read directly from the boat monitoring table shown on the right of Fig.3.1. The TWA can be calculated using 3.1 and 3.2, where γ = tack/gybe angle.

$$TWA = 90 - \gamma/2, \text{ for } TWA < 90 \quad (3.1)$$

$$TWA = 90 + \gamma/2, \text{ for } TWA > 90 \quad (3.2)$$

The tack/gybe angle (γ) is obtained by measuring the angle between the boat's course before and after the tack/gybe, as shown below in Fig. 3.1. This assumes that:

1. After each successive tack/gybe the TWA is the same. It should be noted that after tacking, the skipper will often bear away to increase the TWA and therefore boat speed before coming up to the TWA with the greatest VMG. Similarly when gybing the skipper will often decrease TWA to increase speed after the gybe, this can be seen below in Fig. 3.1.

2. The wind variation in both speed and direction is minimal between tack/gybes.

3. Boat speed and therefore VMG is the same on both tacks/gybes.

4. The skipper is sailing at the TWA of greatest VMG on both tacks/gybes.

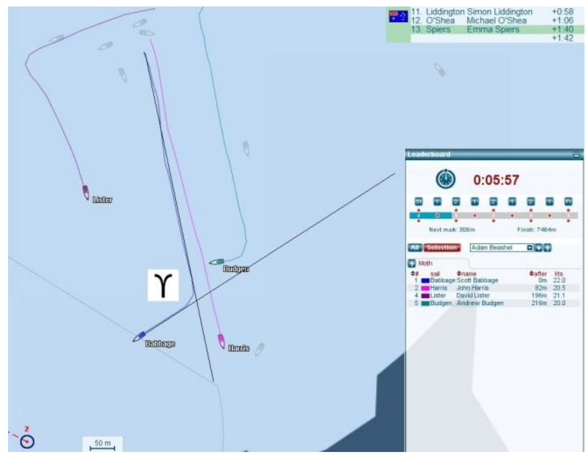

Figure 3.1.: GPS track screen shot, TracTrac [2011]

Wind data has been obtained from weather history from Wunderground [2010]. This website allows historical weather data to be seen from many weather stations around the world. The date and time of day of the race was determined using the sailing instructions issued to the competitors at the beginning of the regatta, Yachting [2010]. The weather station used is located at Potts Point, Sydney, less than three kilometres from the moth course at sea level. The wind data obtained is shown below in Fig. 3.2.

Figure 3.2.: Potts point wind data, 08/12/2010, Wunderground [2010]

Wind and boat data was gathered over the two days in which the moth class raced, however due to discrepancies in the wind/boat data, the data from the second day of racing was disregarded. A typical moth race consists of a windward/lured course, this means only data for two TWA's could be obtained and therefore only two points on the moth VPP could be validated. Tab. 3.1 below shows the validation data used.

Table 3.1.: Validation data

Wind Speed, V_w (kts)	True Wind Angle, TWA (◦)	Boat Speed, V_s (kts)
22.59	48	12.40
22.59	47	12.68
22.59	143	20.27
22.59	143	18.87

3.2. Comparison Of Moth Data to VPP Data

The moth VPP was run with both four and five DOF VPP's, the results can be seen below in Fig. 3.3. It can be seen in Fig. 3.3 below that the five DOF VPP is very unstable for TWA's greater than 140 ◦, this is due to a varying pitch angle. This has not affected the results as the points on the VPP curve to be compared are those where there is a sharp loss of boat speed with a small change in TWA. The skipper's weight and rudder foil elevator flap adjustment would normally stabilise pitch angle, however this did not work due to the high wind speed the VPP was tested at. The VPP was run without the use of the adjustable elevator flap on the rudder foil, this was stabilise the program when using pitching moments. Due to limited validation information available with both accurate weather and boat data, it was not possible to validate the moth VPP at a lower wind speed.

From Fig. 3.3, the boat speed and TWA errors are estimated for both windward and leeward sailing conditions in both four and five DOF VPP's in Tab. 3.2 and Tab. 3.3 below.

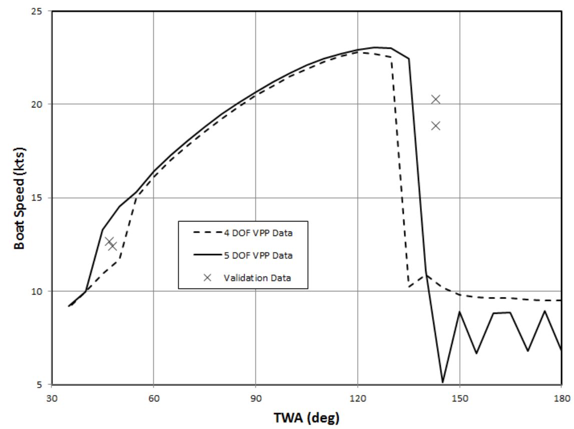

Figure 3.3.: Moth VPP validation

The windward boat speed error is described in Tab. 3.2 shows boat speed is slightly under estimated by the four DOF VPP and over estimated by the five DOF VPP. In leeward conditions the boat speed is over estimated in both cases.

Table 3.2.: Boat speed error

Condition	4 DOF Error (kts)	4 DOF Error (%)	5 DOF Error (kts)	5 DOF Error (%)
Windward	-1.0	-8.0	+1.0	+8.0
Leeward	+3.0	+13.0	+3.0	+13.0

The windward true wind angle error is described in Tab. 3.3 shows TWA is over estimated for the four DOF VPP and under estimated for the five DOF VPP. In the leeward sailing condition the TWA is over estimated in both cases.

Table 3.3.: True wind angle error

Condition	4 DOF Error (◦)	5 DOF Error (◦)
Windward	+5	-5
Leeward	-8	-16

A description of the effects of differing DOF VPP's can be found in sec. 4.1. This section describes the effects of DOF on the VPP's boat speed and true wind angle outputs.

As moth's sailing a windward/leeward course will always sail at the TWA corresponding to their maximum VMG, reference points for both speed and TWA have been taken about these points of maximum VMG. Had this not been taken into account, it can be seen from Fig. 3.3 that the boat speed discrepancy particularly on the leeward data would give an error of $\approx -70\%$. However, a small decrease to the TWA would tend to overestimate the boat speed by $\approx +10\%$, this is due to the rapid speed increase as the boat lift up on the foils.

4. Results

4.1. Variation Of The Degree Of Freedom

The degree of freedom (DOF) of the VPP model has been varied to determine the effect on the output of the VPP. The minimum DOF for a VPP is typically considered to be three (F_X, F_Y and M_X), Larsson and Eliasson [2007] however due to the complex nature of the hydrofoil moth a VPP this simple would be not accurate enough. As the moth typically sails completely supported by foils, it is considered necessary that these forces should be modelled in the simplest form of VPP. Therefore considering a four DOF (F_X, F_Y, F_Z and M_X) VPP as the most basic scenario.

The trim variable deltaFlap has not been used in these simulations as it made the program unstable in fully foiling conditions. This did not alter the results significantly as the MassMove trim variable was still able to trim the boat to optimize the pitch and therefore maximise lift for each condition.

Four Degree Of Freedom Velocity Prediction Program

The four DOF VPP is run as mentioned previously, simulating forces in all x, y and z directions and the heeling moment, (F_X, F_Y, F_Z and M_X). Fig. 4.1 below shows the four DOF VPP run at two wind speeds. This VPP simulation does not take into account the boat's pitch, this has a great effect on the lifting foil's ability to produce lift at low boat speeds. It can be seen above in Fig. 3.3 that the moth's boat speed can be under estimated significantly by this VPP, in windward conditions, and overestimated in leeward sailing conditions. This is due to the variation of the TWA at which the boat can lift out of the water, denoted by the sharp increase in boat speed with variation in TWA. Fig. 4.4 below shows the variation in TWA between four and five DOF VPP's.

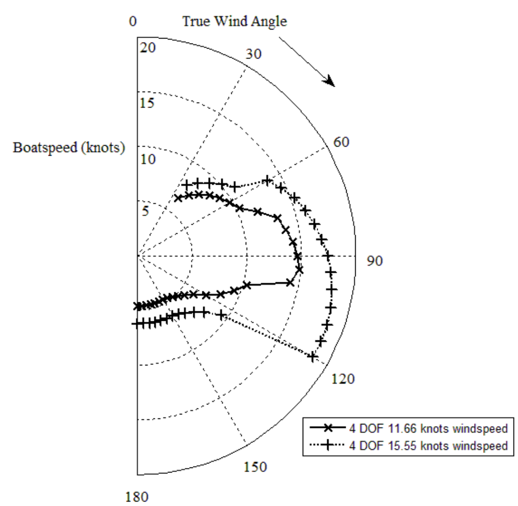

Figure 4.1.: Four DOF moth VPP

Five Degree Of Freedom Velocity Prediction Program

The five DOF is run as mentioned previously, simulating forces in all x, y and z directions as well as the heeling and pitching moments, (Fx, F_Y, F_Z, M_X and M_Y). Fig. 4.2 below shows the five DOF VPP run at two wind speeds. This

VPP simulation does take into account the boat's pitch, this has a great effect on the lifting foil's ability to produce lift at low boat speeds. This can be seen as the variation of the TWA at which the boat can lift out of the water, denoted by the sharp increase in boat speed with variation in TWA. It can be seen above in Fig. 3.3 that the moth's boat speed can be overestimated significantly by this VPP, in both windward and leeward sailing conditions. Fig. 4.4 below shows the variation in TWA between four and five DOF VPP's.

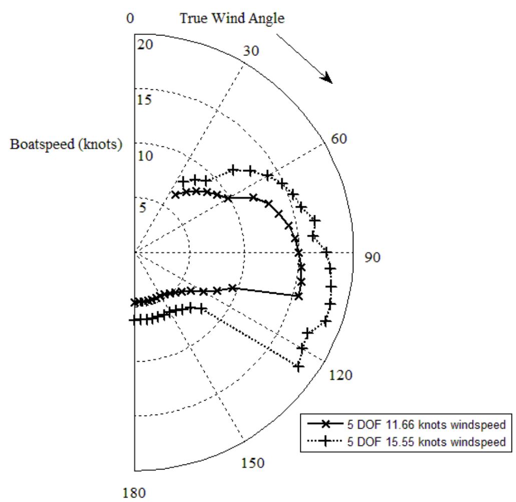

Figure 4.2.: Five DOF moth VPP

Fig. 4.3 below shows the results when the five DOF VPP is run using the deltaFlap trim variable. This variable allows the skipper to control the angle of the elevator flap on the rudder foil, adjusting the boat's pitch to decrease the take-off boat speed. When in use the flap angle is adjusted to minimise foil drag when take-off speed is insufficient and maximise lift when the boat has sufficient speed to take off. However, problems with program stability occur at wind speeds greater than 6m/s, this could be solved by introducing a function which limits the use of this trim function to only non-foiling and take off conditions.

Other VPP outputs such as heel angle also follow trends as seen in practice such as a windward heel angle when sailing to windward. This backward heel angle helps the main foil produce lift to windward in high flying conditions as very little centreboard area remains submerged.

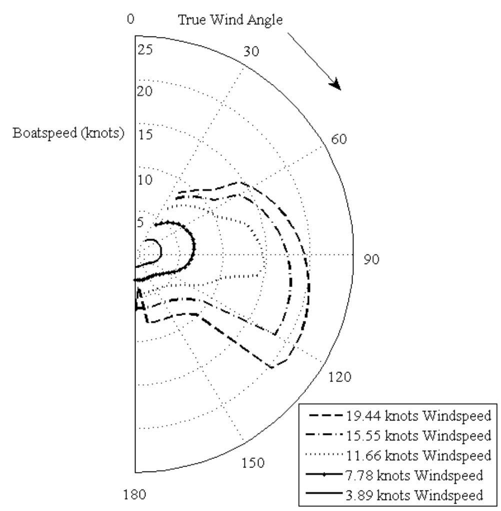

Figure 4.3.: Five DOF moth using deltaFlap trim variable

Six Degree Of Freedom Velocity Prediction Program

The six DOF is run as mentioned previously, simulating forces and moments in all x, y and z directions, (F_X, F_Y, F_Z, M_X, M_Y and M_Z). This VPP solves for forces and moments in all six DOF, taking into account the longitudinal centres of effort for both the foils and sail. A six DOF VPP can determine the required rudder angle at a specific TWA and wind speed. Studies on this VPP have been omitted due to their complex nature, however it should be noted that in most sailing conditions the imbalance of the yaw moment, Mz was minimal, suggesting added drag due to the rudder angle component would be minimal.

This DOF is required if in-stationary simulations are to be run.

Comparison Between Four & Five Degree Of Freedom Velocity Prediction Program

A comparison between a four and five DOF VPP has been carried out to show the variations between the two. Fig. 4.4 below shows the comparison, note that the five DOF VPP will remain flying at lower and higher TWA's as compared to the four DOF VPP. The pitch angle altered by the five DOF VPP creates higher lift from the lifting foils to allow the boat to fly through a broader range of TWA's. This is a far more realistic situation as compared to the four DOF VPP as the skipper will alter their weight position and the elevator flap on the rudder foil to maximise the lift produce by both of the lifting foils.

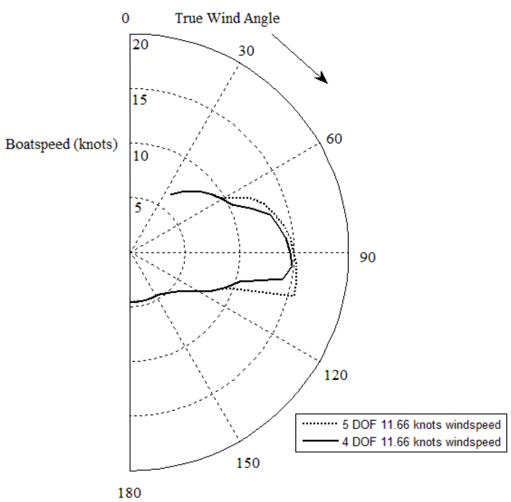

Figure 4.4.: Four & five DOF moth VPP

4.2. Variation Of Foil Lift to Drag Ratios

The lift to drag ratios of both the main and rudder foils have been varied to determine their effect on the VPP results. For this experiment the lift and drag coefficients for the lifting foils were input directly, the reduction in lift due to both the wand and the foil proximity to the surface is determined by a separate function LiftFact which has been estimated by the function of the wand as well as the influence of the free surface. This function is set to unity for all other tests.

As seen below in Fig. 4.5 below, an increase in L/D ratio will tend to increase the TWA at which the moth can take off. This allows the boat to run deeper and still remain on the foils, therefore increasing the downwind VMG. The VPP was not able to solve the similar scenario at lower TWA's, however it is assumed that a similar scenario would occur to that shown below in Fig. 4.5, allowing the boat to remain flying at lower TWA's and therefore increase the windward VMG.

As a design tool, this shows that variations in foil properties will have little effect on the moth's foiling and non-foiling speed. Therefore, to improve the moth's speed, focus should be on improving the aero dynamic efficiencies of the hull and rig. That is, increasing the driving force with respect to the side force produced by the rig and also decreasing windage drag.

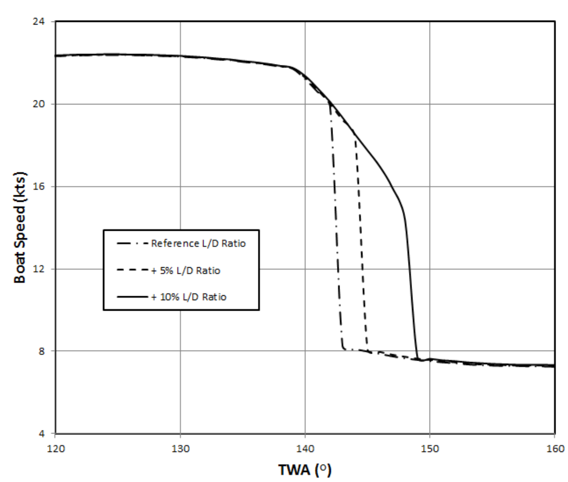

Figure 4.5.: Variation of L/D ratios

5. Conclusion

A VPP is common practice in predicting the performance of a sailing boat in a range of conditions and can be used for both design and improvement purposes. As a platform for the development of a high speed sailing velocity prediction method, it is a good solid start. The VPP developed has the ability to predict the performance of an International Moth Class dinghy with good accuracy. Improvements have been made over existing foiling moth VPP's, this has been achieved in the way of simplifying the foil force model to allow the FutureShip solver to solve for all sailing conditions, both foiling and non-foiling. Two additional degrees of freedom have been used, being both heel and pitch. These are critical components as discussed in subsection 4.1.2.

The over estimation of boat speed on both windward and leeward courses may be explained by an overly efficient rig or insufficient drag produced by hull and rig windage, as shown in section 4.2. Hydro dynamic efficiency was not considered as it is minimal in any circumstance, as only the lifting foils and a small portion of the strut are producing hydro dynamic drag and the aero dynamic drag is by far the major contributor to drag in the foiling condition.

The variation in TWA for windward courses could also be attributed to insufficient aerodynamic drag, as an increase in windward resistance will tend to increase the TWA for which the greatest VMG occurs, as discussed in chapter 3. The variation in leeward TWA could be explained by the hysteresis effect, as FutureShip Equilibrium calculates sailing conditions for TWA's in descending order. This could introduce errors in TWA for which the greatest leeward VMG occurs. As it is common for a skipper to decrease TWA to gain speed before being able to bear away to the TWA for the fastest VMG. This small variation in TWA is to allow the boat to take off, sharply increasing boat speed, allowing the boat to remain flying at greater TWA's.

The VPP is capable of predicting the performance of an International Moth Class dinghy. As a design tool, this VPP has shown the performance of a moth can be improved by increasing the foils L/D ratio, as shown in section 4.2. Allowing the moth to increase VMG when sailing both to windward and leeward. As shown in Figure 4.5 the moth's foiling and non-foiling are independent of L/D variations of the lifting foils. As discussed in section 4.2, the performance of the moth is dependent on the aero dynamic efficiencies of the hull and rig.

References

B. Beaver and J. Zseleczky. Full scale measurements on a hydrofoil international moth. *Chesapeake Sailing Yacht Symposium*, 2009.

J. R. Binns, P. A. Brandner, and J. Plouhinec. The effect heel angle and freesurface proximity on the performance and strut wake of a moth sailing dinghy rudder t-foil. *High Performance Yacht Design Conference*, 2008.

C. Bogle. Evaluation of the performance of a hydro-foiled moth by stability and force balance criteria. Master's thesis, TU-Berlin, 2010.

J. P. Breslin and R. Skalak. Exploratory study of ventilated flows about yawed surface-piercing struts. Master's thesis, Stevens Institute Of Technology, 1959.

Claughton, Wellicome, and Shenoi, editors. *Sailing Yacht Design*. University Of Southampton, 1998.

J. A. Emonson. An investigation into the effect of froude, weber and cavitation numbers on ventilation of surface piercing t-foils. Master's thesis, The Australian Maritime College, 2009.

M. W. Findlay and S. R. Turnock. Development and use of a velocity prediction program to compare the effects of changes to foil arrangement on a hydro-foiling moth dinghy. Master’s thesis, University Of Southampton, 2008.

GmbH FutureShip. *FS-Equalibrium User Manual*, 2010.

M. Grimm. 2011 moth worlds - photo album, 2011.

Hydroptere. The sailboats - l’hydroptere, 2010. URL http://www.hydroptere.com/index.php?page=l-hydroptere-en---presentation.

Australia IMCA. International moth class association of Australia - about, 2008. URL http://www.moth.asn.au/moth/?page_id=2.

ISAF. *International Moth Class Rules*. International Sailing Federation, 2007.

L. Larsson and R. E. Eliasson. *Priciples of Yacht Design*. McGraw Hill, 2007.

C. A. Marchaj. *Sail Performance - Techniques To Maximise Sail Power*. Adlard Coles, 1996.

Mothosphere. Foils history, 2010. URL http://wiki.mothosphere.com/index.php?title=Foils.

D. Schmidt. Learning to fly, 2007. URL http://www.sailmagazine.com/racing/learning_to_fly/.

TracTrac. Tractrac - live gps tracking, 2011. URL http://www.tractrac.com/.

Wunderground. Wunderground weather history, 2010. URL http://www.wunderground.com/.

NSW. Yachting. Sail Sydney - sailing instructions, 2010.

Author Bios

Dane Hull is a graduate of the Australian Maritime College with a Bachelor in Engineering (Naval Architecture), 2011.

Dane’s career is currently focused on building naval ships for the Australian Defence Force.

Dane is a keen sailor, regularly competing in Australia’s famous Sydney to Hobart Yacht Race. He currently races A Class catamarans, which are currently undergoing development within the class to foil, similar to the moth class several years ago. He has plans to further develop this work to apply to the design and development of the foiling A Class.